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COMPARISON OF HEAD AND EYE TRACKING WITH AND WITHOUT A VISUAL CUE TO HEAD POSITION

A Thesis

Presented in Partial Fulfillment of the Requirements for

the Degree of Masters of Science in the

Graduate School of The Ohio State University

By

Nicholas Gerard Luthman, B.S., O.D.

*****

The Ohio State University
2001

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ABSTRACT

Little is known about the ability of humans to pursue pseudo-random targets with the head. This has important implications in the design of head-steered machinery. The purpose of this study was to determine the effect of a visual cue to head position on gaze and head pursuit.

Eleven subjects (3 females, 8 males) were studied as they tracked a pseudo-random horizontal one-dimensional laser target. The target consisted of the sum of six sinusoids. The frequency of the sinusoids was varied from 0.24 and 1.25 Hertz and each sinusoid had a randomly selected amplitude between 0.5 and 12 degrees. Three trials were run on each subject. For the first trial (Condition 1), each subject was instructed to follow the pseudo-random target using any combination of eye and head movement.

In the next two trials, subjects were told to either track the target with the head (Condition HT) or to maintain a head-fixed laser on the target (Condition HR). The order of trial two and trial three was randomized.

Gaze and head position signals were digitized at 200 Hertz using scleral search coils. The mean difference between head and target positions was 8.55 ± 1.15 degrees (Condition HT) and 8.99 ± 0.74 degrees (Condition HR). The mean head velocity gain was -0.33 ± 0.59 (Condition HT) and -0.57 ± 0.43 (Condition HR). The mean difference between eye and target positions was 6.03 ± 1.08 degrees (Condition HT) and 7.52 ± 0.89 degrees (Condition HR). The mean gaze velocity gain was 0.37 ± 0.51 (Condition HT) and 0.33 ± 0.46 (Condition HR). The mean head position differences were not significantly different for the two conditions. The mean eye position difference was

significantly better in Condition HT than in Condition HR. The results indicate that a visual cue to head position did not improve head pursuit performance, was detrimental to eye pursuit performance.

Furthermore, performance with the eye was always better than the head, implying that visually coupled machines should utilize eye tracking rather than head tracking.

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Publications

1. Luthman, N.G. and Fogt, N.F., "The Effect of a Visual Cue To Head Position on Head-Free Pursuit." Optometry and Vision Science, 77(12s), 236, (2000).

2. Fogt, N.F. and Luthman, N.G., "The Effect of a Visual Cue To Head Position on Eye and Head Pursuit." Aviation, Space, and Environmental Medicine, 72(3), 257, (2001).

FIELDS OF STUDY

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CHAPTER 1

INTRODUCTION

1.1 Purpose

In orienting to or following targets, humans often use combinations of eye and head movements. However, little is known about the ability of humans to pursue pseudo-random targets, such as those produced using the sum of several sinusoids, with a free head. This has practical implications in the design of head-steered weapons systems (So et al, 2000). For example, visually coupled systems (VCS), which control instruments that are activated by head or eye movements, have been designed to aim missiles based on measurements of the position of the line-of-sight (Shirachi et al, 1978). The purpose of this investigation was to measure head tracking ability and the effect of a visual cue to head position on head-free pursuit of a pseudorandom target as well as to compare eye pursuit performance to head pursuit performance.

1.2 Eye-Head Pursuit Tracking

It is appropriate to begin by describing the eye and head movement systems that are likely to be involved in head-free pursuit. The eye has two subsystems developed to shift gaze. The ocular smooth pursuit system can sustain accurate tracking up to target frequencies of about 1Hz and at peak velocities of target motion up to 75 degrees per second (Buizza et al, 1986). The role of the ocular smooth pursuit reflex is to follow the target trajectory or to maintain fixation on the target (Gresty et al, 1977). The primary stimulus for smooth pursuit eye movements is target velocity error or a response to the

motion of a target's image across the retina. In addition to the pursuit system, there is a saccadic system, which can "jump" the eye from location to location at velocities as high as 500 degrees per second (Leigh & Zee, 1999). These high-velocity eye movements are used to foveate objects of interest. Most naturally occurring saccades are less than 15 degrees in amplitude (Bahill et al, 1995). The primary stimulus for a saccadic eye movement is retinal position error (Alpern, 1969).

In addition to eye movements, head movements may also contribute to pursuit tasks. In a study of smooth pursuit head motion, the head movement system bandwidth was found to be 2 Hz for both vertical and horizontal axes (Shirachi et al, 1978). There is usually a phase lag that occurs with head pursuit, which tends to increase as pursuit accuracy deteriorates at higher frequencies (Collewijn et al, 1982). Coupling of the eye and head during combined movements will be discussed in the next section.

1.3 Target Stimulus Patterns

Simple sinusoidal stimulus patterns and complex or random patterns usually consisting of the sum of sinusoids of several frequencies have been used to study the dynamic response of the ocular pursuit system.

1.4 Gaze-holding eye movements in eye-head pursuit

Humans can employ a combination of eye and head movements in tracking a target. When the head acts in conjunction with the eye to pursue a small target moving in the visual field, there is an antagonism between the ocular pursuit reflex, which follows the target trajectory, and the optokinetic and vestibulo-ocular reflexes, which operate to stabilize the eyes with respect to the visual field (Gresty et al, 1977). The vestibular system produces compensatory eye movements for brief, transient head movements. These compensatory eye movements, collectively called the vestibulo-ocular reflex (VOR), are initiated to cancel head movement and to maintain a fixed position of gaze. It has been shown that an optokinetic following response, generated when there is not a distinct pursuit target like, for example a textured background, can significantly affect pursuit response. An optokinetic following response can become an optokinetic nystagmus (OKN) if a textured background or a vertical pattern elicits this response, which has a fast phase in the opposite direction and a slow phase in the same

direction as the vertical pattern eliciting the OKN. The OKN can affect pursuit response by improving the gain if the OKN is in the same direction as the target and impairing the gain if the OKN is in the opposite direction (Yee & Daniels et al, 1983).

The vestibulo-oculo reflex (VOR) has a very short latency of approximately 15 msec (Leigh & Zee, 1999, Tabok et al, 1994). The VOR is an extremely important visually stabilizing mechanism during locomotion activities such as walking during which it generates compensatory eye movements for head movement incurred when the heels strike the floor (Leigh & Zee, 1999). However, if the eye and head are going to combine to pursue a target, the VOR must be negated by suppression or by cancellation (Robinson, 1982). It is now believed that during eye-head pursuit, the signal for the VOR from the vestibular neurons is cancelled by a smooth pursuit signal (Huebner et al, 1992). VOR cancellation is only effective at target frequencies less than 1 Hz where the smooth pursuit signal accurately maintains the eye on a pursuit target. Above 1 Hz, the smooth pursuit reflex declines and therefore the cancellation of the VOR breaks down. However, gaze errors, or the position of the eye in space, are generally not affected in this case because saccades supplement the faltering VOR. However, if you lose fixation the VOR takes over. Nevertheless, vision may be affected due to the high retinal image velocity associated with saccades. As head movement is deliberately increased in an eye-head pursuit task, the VOR must be invoked to a larger degree than otherwise which leads to retinal position errors which, leads to more correcting saccades. In my eye-head pursuit experiment, conditions that elicit more movement of the head produce more correcting saccades.

1.5 Objectives

The following objectives were addressed during the experiments. (1) The effect of the VOR was measured by comparing normal gaze accuracy with normal eye-head coordination (Condition 1) to the head tracking condition (Condition HT) during which the head alone was forced to pursue the one-dimensional stimulus target. (2) Head performance was monitored and quantified with no visual cue during Condition HT. (3) Head performance was monitored and quantified with a visual cue during Condition HR (Head Reticle) in which a helmet-mounted laser gave the subject a visual cue to

head position. (4) Head pursuit performance was compared with (Condition HR) and without (Condition HT) a visual cue while tracking the one-dimensional target. (5) Eye position performance was monitored and quantified during each of the three conditions (Condition 1, Condition HT, & Condition HR). Finally in objective six, eye-tracking performance in Condition 1 (no head movement) was compared to head-tracking performance in Conditions HT and HR.

In the following eye-head pursuit tracking experiments described in this thesis, a pseudorandom one-dimensional horizontal target was used to make the comparisons mentioned above. I hypothesized the following. (1) The VOR should have little effect on eye-tracking based on previous literature (Collewijn et al, 1982). (2) Head-tracking would be better with a visual cue (Condition HR) than without a visual cue (Condition HT). (3) Gaze accuracy should not be affected during head-tracking with (Condition HR) and without (Condition HT) the head reticle because the extent of head movement is likely to be similar in the two conditions.

CHAPTER 2

MATERIALS AND METHODS

2.1 The Scleral Search Coil Method

Eye and head positions were measured using the scleral search coil method (Robinson, 1963). The magnetic field coils used in this experiment were obtained from C-N-C Engineering (C-N-C Engineering, Seattle, WA). The field coils were 3 feet in size. This equipment provided three-dimensional (horizontal, vertical, and torsional) measurements of head and two- dimensional (horizontal, vertical) measurements of eye position. The bandwidth of this system was 80 Hz (– 3 dB). The noise level was calculated to be approximately 15 minutes of arc. This was the standard deviation of the digitized signals recorded over 3 seconds on a stationary artificial eye. The magnetic field was uniform enough that small translations of the head did not affect calibration of the coil signals. For horizontal positions, the magnetic field had homogeneous gain (< 5% change) within 10 cm on either side of the center of the magnetic field.

The subject was placed within this magnetic field and wore an annular silicone contact lens (search coil) on the right eye (Skalar Medical, Delft, Netherlands). Prior to placing the search coil on the subject's right eye, one drop of anesthetic (Proparicaine) was instilled into the eye. The silicone annulus had a coil of wire embedded within it such that when the eye (or head) was rotated within the magnetic field, a voltage was induced within the coil. This voltage was proportional to the sine of the angle between the axis of the eye coil and the direction of the magnetic field. In addition to the eye

coil, a second Skalar coil was firmly attached to an adjustable, tight-fitting, lightweight, binocular indirect ophthalmoscope helmet. This coil was placed on the center of the subject's forehead to monitor head position (Huebner et al, 1992). This head coil was capable of measuring horizontal and vertical movement and had a second coil of wire wound in the sagittal plane to measure torsion.

2.2 Calibration Procedures

The search coil apparatus was calibrated by placing an artificial eye (supplied by C-N-C Engineering, Seattle, WA) in the magnetic field in a position close to that of the subject's right eye. The artificial eye had a coil of wire wrapped within it. A 12-bit analog-to-digital converter recorded the digitized signals for the calibration and for the experiments (Measurement Computing, Model CIO-DAS08). For the calibration, digitized signals were recorded as the artificial eye was rotated in 5-degree increments over a range of ± 25 degrees. The horizontal eye gain was 62.7 bits per degree. To ensure that the coil used on the eye and the head had the same gain as that of the artificial eye, another calibration was obtained with a non-torsional coil identical to that placed on the eye. Potential differences in the gain could have occurred as a result of variations in coil diameter or variations in number of turns in the coil. The gain of the eye coil was within 3 percent of the gain of the artificial eye. Finally, another calibration was obtained with a torsional coil identical to that placed on the helmet to measure head movement. The gain for this coil was within 3 percent of the gain obtained with the artificial eye.

2.3 Experimental Designs Methods-The Stimulus Target

The target for the head and eye pursuit testing experiment was a red (compact laser diode) laser spot, approximately 3 mm in size (Imatronic Limited, 670 nm, Herts, England). The target was projected from behind the subject onto a screen about 1.50 m from the eyes at a height of 134.3 cm from the floor. The height of the target was approximately at eye level for the seated subject. The target was projected onto a flat, featureless, black background in order to avoid generating a potential optokinetic reflex eye movement (OKN) response due to the background (Gresty et al, 1977). The target motion was produced by reflecting the red laser spot off of a mirror attached to a

servo-controlled galvanometer (General Scanning, CX-660, Watertown, MA). The bandwidth of the galvanometer was 150 Hz. The galvanometer input was supplied by a computer using a 12-bit digital-to-analog (D-A) converter. The computer supplied the digitized values associated with the voltages necessary to rotate the galvanometer mirror to produce the pursuit target. This computer was not the same as that used to record the voltages from the eye and head coils. To calculate the target gain, known D-A voltages in 0.25 v increments were fed into the computer controlling the galvanometer and the lateral position of the laser spot target was measured and converted to degrees. Then a graph of the angle of rotation of the laser spot versus D-A value was prepared. Using regression analysis, the gain or slope of the aforementioned graph for the galvanometer target was 33.7 degrees per volt. The regression analysis showed that the correlation coefficient associated with the graph was 97.8 percent over the $\pm$ 25-degree one-dimensional horizontal field. The frequencies summed to generate the pseudorandom pursuit target in this experiment were as follows: 0.24 Hz, 0.37 Hz, 0.50 Hz, 0.78 Hz, 1.00 Hz and 1.25 Hz. Amplitudes randomly assigned to these frequencies to produce the pseudorandom target were as follows: 12°, 9°, 6°, 3°, 1°, and 0.50° (See Table 1 for amplitude & frequencies of sinusoids combined during each 30 second recording period). There was no phase lag for each of the sinusoids when they were summed.

2.4 Experimental Luminance Conditions

The eye-head tracking experiment was performed in a dark room with background luminance of 0.005 cd/m² as measured with a Pritchard Photometer (Spectra, Pritchard Photometer, Burbank, CA). The luminance of the red laser target was 24.9 cd/m². The luminance of the green laser target used as the visual cue to head position and projected from the subject's helmet, was 248 cd/m² (B&WTEK, 532, Newark, DE). (Figure 6) The *miniBird* receiver was located 1 cm away from the green helmet-mounted laser. The projected green image emitted from the head laser onto the black screen had a diameter of approximately 7.5 mm.

2.5 *The miniBird*-Head Translation Monitoring Device

The *miniBird* is a magnetic tracking device, which measures position and orientation with six degrees of freedom (Ascension Technology, Burlington, VT). The six degrees of freedom include anterior-posterior translation, horizontal translation, vertical translation, horizontal rotation, vertical rotation and cyclorotation. The *miniBird* instrument is very similar to the scleral search coil system. The system has a transmitter that generates a DC magnetic field. When the receiver is rotated, a voltage is generated within the receiver that is proportional to the amount of rotation. Translational measurement from the *miniBird* was especially important because the pursuit target was closer to the subject than infinity, and head translation could possibly have affected the angles of the head and eye rotation required to fixate the target (Epelboim et al, 1995). The *miniBird* has a published translation resolution of 0.02 inches and a published angular resolution of 0.1 deg at 12 inches. Head translation signals from the *miniBird* were recorded from the computer's RS-232 serial port at approximately 60 Hz.

In a separate experiment, the *miniBird* was used to measure head translation while the subjects pursued the pseudorandom laser stimulus target. Again, the subject was fitted with a tight-fitting, lightweight helmet modified from a binocular indirect ophthalmoscope (BIO) and the receiver for the *miniBird* was mounted onto this helmet as close as possible to the approximate horizontal center of rotation of the head (Leigh & Zee, 1999). (Figure 6) The *miniBird* receiver was attached to the helmet with black electrical tape, which eliminated much of the high frequency noise from the search coil apparatus (which was turned on during this supplementary exercise) that would have contaminated the *miniBird* measurement.

2.6 Experimental Procedures

Eleven subjects (3 females, 8 males) ranging from 24 to 57 years of age participated in the experiment described herein. After each subject gave informed consent, he or she was seated on a wooden chair inside the search coil cage apparatus. After the ocular search coil was placed on the subject's right eye (previously described in Section 2.1), the binocular indirect ophthalmoscope (BIO) helmet was adjusted to fit snugly on the subject's head in a position allowing the green head laser to point at the

red target laser centered on the screen. For some subjects, a downward head tilt was required to align the helmet laser with the target laser. As Table 2 shows, the amount of this downward tilt was calculated as the angular difference between the vertical head position without the laser (Condition HT) and the vertical head position with the laser (Condition HR). The downward tilt was calculated in this way because Condition HT demonstrates the subject's habitual vertical head position. Table 3 shows the vertical mean of the head laser calibration position for each subject versus the vertical mean head laser while subjects followed the target during Condition HR. This shows the vertical position of the head when the subject was following the target in these 2 conditions. This difference was on average approximately 1 degree so subjects kept the laser spot at the same vertical position as the target. Similarly, Table 4 shows the angular difference between the vertical eye position without the laser (Condition HT) and the vertical eye position with the laser (Condition HR) for each subject. A difference of zero indicates that the eye rotated upward where necessary (i.e. cases of downward head tilt) so as to be vertically aligned with the target. The mean vertical difference was less than one degree thus demonstrating that the eye fully compensated for the downward head tilt. Table 5 lists the vertical mean of the eye calibration data with the head laser turned on versus the vertical mean eye position during the HR Condition (With the head laser turned on). The mean of Table 5 was also less than one degree demonstrating that subjects maintained the eye at the same vertical position as the target.

The zero horizontal position for each subject was obtained in the following way. Eye, and head, and galvanometer position signals were recorded as subjects pointed their heads at the red target. Signals centered straight ahead of the nose were recorded at 200 Hz for 3 seconds. Next, the eye and head position signals were measured as subjects pointed the green head laser at the centered red target straight ahead of the nose. Signals were recorded at 200 Hz for 3 seconds.

After the calibration procedure was complete, the subject performed three tracking conditions. During the first condition, the green head laser was turned off, and the subject was instructed to follow the red laser target any way he or she saw fit. A

separate computer drove the trajectory of the pseudorandom laser target, which was the same during each of the three conditions. The target began straight ahead of the subject's nose and began to move when the investigator started the appropriate computer code. At the same time the computer code used to record the galvanometer target, head and eye signals was started. After the subject followed the target for 10 seconds, galvanometer, head, and eye signals were recorded for 10 seconds. A period of 30 seconds followed during which the subject pursued the target but search coil and galvanometer target signals were not recorded. This cycle was repeated 3 more times throughout the duration of the trial.

Next, one of two pursuit tasks was performed. The order of these tasks was randomized for each subject. In one condition, subjects tracked the pseudorandom target with the green head laser turned on (Condition with Head Reticle [HR] - with the visual cue) and in the other condition, he or she pursued the red target without the green head laser turned on or with their head only (Condition Head Tracking [HT] - without the visual cue).

Condition HT for subject DW was performed after a several hour delay. This was because after the second trial, the head coil wire was broken. The target, head, and eye positions were recalibrated prior to the completion of Condition HT.

After the last condition was completed, the subject's right eye was viewed with a biomicroscope and then observed again after instillation of Sodium Fluorescein. This procedure was done to ensure that no corneal epithelial disruption or corneal fluorescein staining had occurred with the scleral search coil.

2.7 Supplemental Experiment - Translation Measurement

As mentioned in Section 2.5, a supplemental experiment was performed in which the *miniBird* device was used to measure head translation. Nine subjects (1 female, 8 males) ranging from 24 to 39 years of age participated in this experiment. Four of the nine had participated in the initial experiment described in Section 2.6 (Subjects: JC, JS, MA, RS). The translation data are listed in Table 8. Again, translation could be important because the laser target was closer to the subject than infinity, so

head translation could possibly have affected the angles of head and eye rotation required to fixate the target (Epelboim et al, 1995). Subjects signed the informed consent. They were then seated on the same wooden chair described earlier inside the search coil magnetic field cage apparatus. The lightweight BIO helmet was placed on the subject's head. The *miniBird* receiver was mounted on this helmet with electrical tape as close as possible to the approximate center of rotation of the head (Leigh & Zee, 1999). The green head laser was 1 cm right of the *miniBird* receiver. The subject then followed the same pseudorandom laser target used in the main experiment with the head laser. The target began straight ahead of the subject's nose and eye movements were recorded at similar intervals to those of the main experiment.

CHAPTER 3

RESULTS

3.1 Data Analysis

I. Calibration

The galvanometer target, horizontal head, and horizontal eye positions were calibrated by subtracting the mean of the appropriate zero value from the calibration and dividing this difference by the appropriate gain.

II. Compensation of galvanometer target position for differences in the center of rotation (COR) of the head and eye

In analyzing these data, it is necessary to account for the difference in location of the centers of rotation (COR) of the eye and head. This could lead to differences in the rotational demand of the targets for the eye and the head. The center of rotation of the eye is approximately 14.8 mm behind the cornea (Fry et al, 1962) and the center of rotation of the head is approximately 10 cm behind the eye (Leigh & Zee, 1999). To account for the differences in the locations of the COR of the eye and the COR of the head for the target at 1.50 m, the COR of the head was assumed to be 155 cm from the screen and the COR of the eye was assumed to be 145 cm from the screen. Therefore, the relative angular galvanometer target position for the head (G_H) was calculated as follows: G_H = galvanometer position x .97. Likewise, the relative galvanometer target position for the eye (G_E) was calculated as follows: G_E = galvanometer position x 1.03.

III. Compensation for eye translation due to head rotation

Because the eye is laterally displaced from the horizontal center of rotation of the head, which is along the midline, there is lateral translation of the eye associated with rotation of the head. This eye translation was accounted for in the data analysis. Assuming an interpupillary distance of 6 cm, for each 1 degree of head rotation, the eye translated 0.1745 cm. This amount of eye translation is equivalent to 0.067° for each 1° of head rotation demand. This 0.067° was multiplied by the calibrated horizontal head rotation angle, and then added to the associated horizontal eye position to become the corrected horizontal eye position.

3.2 Vertical and Cyclorotation Standard Deviations

Table 6 lists the vertical head standard deviations for Condition HT (without Laser) and Condition HR (with Laser). The mean of the standard deviations for both conditions was less than 1 degree, which is very small. Table 7 lists the cyclorotational standard deviations for the head for the above conditions and again, the mean of the standard deviations were both negligible (approximately 1.5 degrees). Since both vertical and cyclorotational effects were small, no correction was made for goniometric or kinematical artifacts associated with head cross-coupling because three dimensional motions of the head did not occur with the one-dimensional target motion (Ferman et al, 1987, Larsen et al, 1988).

3.3 Head translation

Head translation was measured in the supplemental experiment. I assumed that when the head rotations were recorded, the target parameters were similar in the main experiment and in the supplemental experiment. This required that the *miniBird* recordings begin at the same time as the search coil recordings. Figure 1 demonstrates the excellent temporal synchronization of the two recording methods to measure head position. Table 8 lists the mean change in rotational target demand due to head translation for each subject. The average change in rotational demand brought about by head translation was 0.16 ± 0.05 degrees. This value was also negligible so there was no need to compensate any further for head translation.

3.4 Analysis of Horizontal Eye & Horizontal Head, and Target Position

To demonstrate the accuracy of eye and head tracking, differences between the head and target and the eye and target were measured. Table 9 lists the means and standard deviations of the horizontal eye and target differences for each subject for the three conditions. From this table, the mean and standard deviation was 5.93 ± 1.22 degrees for Condition 1, 6.03 ± 1.08 degrees for Condition HT, and 7.52 ± 0.89 degrees for Condition HR. The results for the three conditions were compared using repeated measures ANOVA. The two variables in the ANOVA Model were condition and subject. Using the results of the ANOVA, the means for each condition were compared using The Tukey Method of Multiple Comparisons (α=0.05). Condition 1 and Condition HR were not significantly different, but Condition 1 and Condition HT were both significantly different than Condition HR. Performance was poorest in Condition HR.

Similarly, Table 10 lists the means and standard deviations of the horizontal head and target differences for each subject for the three conditions. Of course, this analysis is invalid if subjects did not actively pursue the target with the head in the HT and HR Conditions. For example, a subject might have moved the head less without the head reticle. This could be a conscious decision based on the subject's expectation that the target must cross the midline at regular intervals. However, it could be an unconscious decision. In the latter case, the subject may simply be unaware that he or she is not following the target motion fully. To determine whether the amplitude of the head movement varied in Condition HR and Condition HT, head position for these two conditions were plotted and compared. All subjects clearly moved the head in both conditions. However, 2 subjects (FC and RS) demonstrated consistently smaller amplitudes of head motion in Condition HT. While we acknowledge that this occurred, the differences in amplitude were not exceedingly large so we included the values for all subjects in our analysis. From Table 10, the mean and standard deviation of each condition was 9.24 ± 0.95 degrees for Condition 1, 8.55 ± 1.15 degrees for Condition HT, and 8.99 ± 0.74 degrees for Condition HR. Repeated measures ANOVA statistical analysis, similar to that used for gaze, was performed and no statistically significant

differences were found. It should be noted that during Condition 1, all subjects, with the exception of subject WB, kept their head stationary and moved their eyes to follow the target as shown by the time versus position graph of subject LM in Figure 3. Figure 2 is the time versus position graph of Condition 1 for subject WB, which shows that this subject initially moved the head early in the trial and later maintained a stationary head position.

In a comparison of differences between horizontal eye and target position versus horizontal head and target position, the eye clearly followed the target more accurately than the head. This was demonstrated by repeated measures Two-factor ANOVA using data from Condition HR ($p < 0.001$). The two factors were subject and head (Head – Target) or eye (Eye – Target). The Two-factor Model ANOVA was used instead of Three-Factor ANOVA with the factor being condition, subject, Head or Eye to avoid potential unnecessary interactions. This is reasonable because the means for Head – Target were about the same (Table 10) for all conditions and the worst mean for Eye – Target was Condition HR (Table 9). Therefore, Condition HR was not likely the condition where Head and Eye Tracking accuracy would be equal. The eye was better in this condition and the eye was better in all three conditions compared to the head.

3.5 Analysis of Eye and Head Velocity Gain

Velocity gain is a common measure used to demonstrate the accuracy of pursuit performance. Eye velocity gain is defined as the eye velocity divided by the target velocity. The horizontal eye velocity (HE_{VEL}) was determined by taking the calibrated eye position difference between successive points and dividing this value by the time interval between them. Similarly, the galvanometer target velocity (G_{VEL}) was determined by taking the calibrated target position differences and dividing by the time interval between them. The horizontal eye velocity gain was thus defined as $HE_{GAIN} = HE_{VEL} / G_{VEL}$. The aforementioned method is the traditional way eye gain is determined. However, the traditional analysis gives undue weight to the lower target velocities calculating the overall mean eye gain. Therefore, a regression analysis was performed with the galvanometer velocity as the predictor and the horizontal eye velocity as the response to determine how faithfully the galvanometer target velocity

was reproduced by the eye. Tables 11 through 13 listed the eye gain data for each subject for each of the three conditions in the experiment. Listed within each table are the results of t-tests, the correlation coefficients (r), and the slope of the associated regression lines. The null hypothesis for this t-test was that there was no linear relationship between the variables. Although the correlation coefficients were very low, there was typically a small positive relationship between the variables (slope) in most cases ($p<0.50$). The correlation coefficient did not seem to vary between conditions for most subjects.

The horizontal head velocity (HH_{VEL}) was determined by taking the calibrated head position difference between successive points and dividing by the time interval between them. Again, the galvanometer target velocity (G_{VEL}) was determined as described above. The head velocity gain is traditionally defined as $HH_{GAIN} = HH_{VEL} / G_{VEL}$. Again, the traditional analysis gives undue weight to the lower target velocities in calculating the overall mean eye gain. Therefore, a regression analysis was performed with the galvanometer velocity as the predictor and the horizontal head velocity as the response to determine how faithfully the galvanometer target velocity was reproduced by the head. Listed in Tables 14 through 16 are the head gain data for each subject during each of the three conditions in the main experiment. Listed within each table are the results of the t-tests, the correlation coefficients (r), and the slope of the associated regression lines. Once again, the correlation coefficients were very low, but there was a small linear relationship between the variables in many cases. The correlation coefficients for the head in Condition HT and Condition HR were similar for most subjects. Some slopes were positive and some were negative. Generally, most subjects demonstrated a positive slope for the eye velocity verses the target velocity plot, but many subjects demonstrated a negative slope for the head velocity versus target velocity plot.

CHAPTER 4

DISCUSSION

4.1 Effect of Head Reticle on Eye - Target Positional Differences and Eye Gain Results

The head reticle seemed to have the greatest deleterious effect on the eye – target position difference. Table 9 shows mean eye – target positions of the three conditions. The greatest mean error, 7.52 ± 0.89 degrees, occurred for Condition HR. The mean eye gain values were worse in the HR Condition than in the HT Condition with and without zero target velocities (Table 12 & Table 13). Presumably, this could have occurred because the HR Condition required more processing time. This increased processing time could be interpreted as a phase lag, which increases because the subject must determine the spatial relationship between the target and the head reticle. The subject may be looking around the reticle position inducing backward saccades or longer pauses between saccades and pursuits. Increased processing time may show up in longer phase lags and further analysis may be required to determine this phenomena. The time versus position graphical analysis plots in Figure 4 and Figure 5 shows data obtained in the main eye-head tracking experiment for subject JC. There appears to be a phase lag between the galvanometer target position and the head position. Saccadic eye movements are apparent in both traces.

Another possibility for the gaze accuracy reduction in Condition HR could have been because different strategies were employed to pursue the target during the two

conditions (Conditions HR and HT). It appears that head movement strategy differs with the head reticle; the head moves to a greater extent to try to follow the target rather than waiting for the target to return from extreme positions. The differing head pursuit strategy may have affected the normal coordination between the eye and the head thus adversely affecting gaze. Thus, gaze position may be worse in the HR Condition because of this difference in head strategy. This may be the reason for the decrease in head gain with the zero target velocities (-0.57 ± 0.43) versus head gain without zero target velocities (-0.39 ± 0.49) in Condition HR

. Also, while it is possible that subjects performed worse in Condition HR because they may have had to turn the eye up if the head was turned down in this condition, it is unlikely that the approximate 6 degree vertical deviation (Table 2) was a major factor. This relatively small vertical deviation is nowhere near the magnitude discussed by Yee, et al in the concept of the pursuit system not being as efficient in eccentric gaze as in primary gaze (Yee & Goldberg et al, 1983).

4.2 Vestibulo-ocular Reflex (VOR) Effects on Eye – Target Differences

The eye – target differences were approximately the same during the first Condition and the HT Condition (Table 9). Again, the head was roughly stationary during the first Condition, and the head was forced to follow the galvanometer target during Condition HT. The similarity in the differences between the two conditions would indicate that the VOR was cancelled or had little effect pursuit. While not specifically addressed, there may have been an increase in the number of saccadic eye movements in Condition HT.

4.3 Effect of Head Reticle on Head – Target Position Differences

As shown in Table 10, the H – T position differences are not significantly different between the HT and HR Conditions. Hence, the head reticle did not hinder the performance of the head to pursue a pseudorandom target. I would speculate that a visual cue to head position might be helpful in a real world visually coupled system such as a cockpit where attention may be divided among several tasks.

4.4 Eye Tracking versus Head Tracking

Statistically, the eye appears to pursue a pseudorandom target significantly better than the head based on the Two-Way ANOVA Model (($p < 0.0001$) from the eye minus target data. Since the eye appears to do a better job of following the target than the head, it may be a better idea to consider using eye-tracking or eye-steered machinery rather than head-steered systems.

4.5 Velocity Analysis

Referring to Tables 11 through 16, it seems that the slope of the eye velocity versus target velocity plots was typically positive while the slope of the head velocity versus target velocity was often negative. This means that the head was often times moving in a direction opposite to that of the target. It is speculated, based on plots such as those of Figures 6 and 7, that this may be due in part to a phase lag associated with the head rather than random departures of head velocity from target velocity. This is because the waveform of the head appears to be similar to that of the galvanometer target. It seems likely however that improvement in eye gain would not be accomplished simply by accounting for a phase lag. This is because saccadic eye movements produce radical departures from unity gain.

This brings up an interesting point for future study. As pointed out by So and Griffin (2000), a number of investigators have studied the influence of predictors of future target motion on head pursuit. From the data presented in this thesis, it seems that providing clues about future target position could perhaps eliminate the phase lag associated with the head. In that case the head may be aligned with the target more often than the eye.

4.6 Summary

These experiments and analyses have compared head and eye tracking with and without a visual cue to head position. In conclusion, the best overall scenario for visually coupled systems may be gaze or eye tracking with no head reticle. Moreover, the VOR has minimal effect on head and eye pursuit performance in the tracking of a horizontal one-dimensional pseudorandom target.

	12°	9°	6°	3°	1°	0.50°
P 1	0.24 Hz	0.78 Hz	0.50 Hz	1.25 Hz	0.37 Hz	1.00 Hz
P 2	0.24 Hz	1.00 Hz	1.25 Hz	0.78 Hz	0.37 Hz	0.50 Hz
P 3	1.00 Hz	0.24 Hz	1.25 Hz	0.78 Hz	0.50 Hz	0.37 Hz
P 4	0.24 Hz	1.00 Hz	0.78 Hz	0.50 Hz	0.37 Hz	1.25 Hz
P 5	1.25 Hz	0.50 Hz	1.00 Hz	0.24 Hz	0.37 Hz	0.78 Hz

Table 1: Amplitudes & Frequencies of Sinusoids Combined during each 30 second Recording Period

SUBJECT	Vertical Head Position Without Laser minus Vertical Head Position With Laser (DEGREES)
DW	8.12
FC	2.67
JC	0.83
JP	12.22
JS	0.32
LM	3.51
MA	3.06
RM	11.46
RS	11.13
TT	6.26
WB	8.07
Column Mean	6.15 ± 4.34

Table 2: Vertical Head Position Differences With and Without Laser

SUBJECT	Vertical Head Position With Laser Calibration minus Vertical Head Position With Laser (Condition HR) (DEGREES)
AB	+0.50
DW	-0.10
FC	+1.5
JC	+1.26
JP	+5.24
JS	+1.08
LM	+0.83
MA	+0.98
RM	+0.66
RS	+0.90
TT	-1.25
WB	-0.01
Column Mean	+0.97 ± 1.54

Table 3: Vertical Head Position Differences With Laser Calibration and With Laser (Condition HR)

+ Indicates that the laser spot is below the target

SUBJECT	Vertical Eye Position Without Laser minus Vertical Eye Position With Laser (DEGREES)
DW	+4.72
FC	-0.19
JC	-0.49
JP	+0.38
JS	+0.20
LM	+0.62
MA	+0.57
RM	-0.70
RS	+0.89
TT	+0.58
WB	+0.13
Column Mean	+0.61 ± 1.45

Table 4: Vertical Eye Position Differences With and Without Laser

+ Indicates that the laser spot is below the target

SUBJECT	Vertical Eye Position With Laser Calibration minus Vertical Eye Position With Laser (Condition HR) (DEGREES)
DW	+0.17
FC	+0.31
JC	+0.31
JP	-6.34
JS	-0.16
LM	-0.09
MA	+1.59
RM	-0.62
RS	+0.42
TT	-0.42
WB	-0.54
Column Mean	-0.49 ± 2.03

Table 5: Vertical Eye Position Differences With Laser Calibration and With Laser (Condition HR)

+ Indicates that the laser spot is below the target

SUBJECT	Vertical Head Standard Deviations (DEGREES)	
	Without Laser	With Laser
DW	0.58	0.69
FC	0.53	1.00
JC	0.77	0.70
JP	0.76	0.85
JS	0.89	0.65
LM	0.87	0.84
MA	0.74	0.39
RM	0.46	0.56
RS	0.71	0.58
TT	0.60	0.95
WB	0.40	0.83
Column Mean	0.66 ± 0.16	0.73 ± 0.18

Table 6: Vertical Standard Deviations Without and With Laser

SUBJECT	Cyclo Standard Deviations (DEGREES)	
	Without Laser	**With Laser**
DW	0.60	1.37
FC	1.34	2.06
JC	1.20	0.99
JP	3.07	1.31
JS	2.62	2.58
LM	1.60	1.83
MA	1.41	0.86
RM	0.89	2.00
RS	0.55	1.29
TT	1.23	0.90
WB	1.08	1.49
Column Mean	1.42 ± 0.78	1.52 ± 0.54

Table 7: Cyclorotational Standard Deviations Without and With Laser

SUBJECT	**CHANGE IN ROTATIONAL TARGET DEMAND DUE TO HEAD TRANSLATION With Laser (DEGREES)**
BE	0.12
BP	0.17
BU	0.20
EW	0.12
JC	0.16
JS	0.16
MA	0.26
NL	0.14
RS	0.12
Column Mean	0.16 ± 0.05

Table 8: Change in rotational target demand due to head translation

SUBJ	EYE - TARGET Condition 1 (Degrees)	EYE - TARGET Without Laser Condition HT (Degrees)	EYE - TARGET With Laser Condition HR (Degrees)
DW	4.90 ± 3.88	4.79 ± 3.99	7.01 ± 5.28 *
FC	7.92 ± 6.28	7.98 ± 6.83	8.35 ± 7.03 *
JC	5.09 ± 3.66	5.12 ± 4.47	6.45 ± 5.15 *
JP	4.46 ± 3.16	5.52 ± 4.72 *	6.52 ± 5.57
JS	8.11 ± 5.85	6.77 ± 5.17	7.80 ± 6.81 *
LM	6.26 ± 3.90	4.78 ± 3.36	6.27 ± 4.98 *
MA	5.75 ± 4.35	6.16 ± 5.14 *	7.52 ± 6.07
RM	5.35 ± 4.18	7.65 ± 5.16 *	8.76 ± 6.36
RS	6.25 ± 5.28	6.42 ± 5.12	7.67 ± 6.64 *
TT	6.42 ± 4.88	6.55 ± 5.18	7.60 ± 6.40 *
WB	4.71 ± 3.85	5.58 ± 4.54	8.78 ± 6.35 *
Col. Mean	5.93 ± 1.22	6.03 ± 1.08	7.52 ± 0.89

Table 9: Eye minus Target Position

NOTE: * Indicates first head tracking condition

SUBJ	HEAD - TARGET Condition 1 (Degrees)	HEAD - TARGET Without Laser Condition HT (Degrees)	HEAD - TARGET With Laser Condition HR (Degrees)
DW	10.10 ± 5.99	7.10 ± 5.66	8.17 ± 5.98 *
FC	9.33 ± 7.40	8.64 ± 7.03	9.76 ± 7.48 *
JC	7.74 ± 6.23	6.68 ± 5.73	8.56 ± 6.33 *
JP	8.98 ± 6.50	10.28 ± 7.29 *	8.66 ± 6.91
JS	10.29 ± 5.92	9.66 ± 6.58	9.52 ± 7.27 *
LM	11.03 ± 9.30	8.53 ± 5.22	8.07 ± 6.28 *
MA	8.46 ± 5.47	10.02 ± 6.36 *	8.62 ± 6.07
RM	9.53 ± 6.04	8.32 ± 5.90 *	8.42 ± 5.65
RS	8.44 ± 6.88	8.58 ± 7.62	9.99 ± 7.57 *
TT	9.11 ± 6.79	8.72 ± 5.71	10.15 ± 6.61 *
WB	8.63 ± 6.37	7.50 ± 5.04	8.95 ± 5.96 *
Col. Mean	9.24 ± 0.95	8.55 ± 1.15	8.99 ± 0.74

Table 10: Head minus Target Position

NOTE: * Indicates first head tracking condition

SUBJ	EYE GAIN DATA T-Test (p-value) Horizontal Eye	EYE GAIN DATA Corr. Coeff. (r) Horizontal Eye	EYE GAIN DATA Slope (m) Horizontal Eye
DW	+21.25 (p< 0.001)	0.43	+0.25 *
FC	+27.25 (p< 0.001)	0.52	+0.46 *
JC	+11.86 (p< 0.001)	0.08	+0.03 *
JP	+17.79 (p< 0.001)	0.37 *	+0.27
JS	-9.15 (p< 0.001)	0.20	-0.17 *
LM	-27.18 (p< 0.001)	0.52	-0.42 *
MA	+18.43 (p< 0.001)	0.38 *	+0.26
RM	+15.56 (+0.003)	0.33 *	+0.22
RS	+34.62 (p< 0.001)	0.61	+0.48 *
TT	+2.71 (+ 0.007)	0.06	+0.03 *
WB	+35.79 (p< 0.001)	0.63	+0.55 *

Table 12: Eye Gain Data for Condition 1

NOTE: * Indicates first head tracking condition

SUBJ	EYE GAIN DATA T-Test (p-value) Horizontal Eye	EYE GAIN DATA Corr. Coeff. (r) Horizontal Eye	EYE GAIN DATA Slope (m) Horizontal Eye
DW	+28.55 ($p < 0.001$)	0.54	+0.38 *
FC	+28.14 ($p < 0.001$)	0.53	+0.41 *
JC	+27.30 ($p < 0.001$)	0.52	+0.41 *
JP	+15.09 ($p < 0.001$)	0.32 *	+0.26
JS	-0.62 (+0.538)	0.00	-0.01 *
LM	-19.66 ($p < 0.001$)	0.40	-0.33 *
MA	+13.44 ($p < 0.001$)	0.29 *	+0.22
RM	+14.60 ($p < 0.001$)	0.31 *	+0.26
RS	+33.00 ($p < 0.001$)	0.59	+0.49 *
TT	+15.53 ($p < 0.001$)	0.33	+0.20 *
WB	+26.20 ($p < 0.001$)	0.51	+0.46 *

Table 12: Eye Gain Data for Condition HT

NOTE: * Indicates first head tracking condition

SUBJ	EYE GAIN DATA T-Test (p-value) Horizontal Eye	EYE GAIN DATA Corr. Coeff. (r) Horizontal Eye	EYE GAIN DATA Slope (m) Horizontal Eye
DW	+12.60 (p< 0.001)	0.27	+0.18 *
FC	+21.23 (p< 0.001)	0.43	+0.33 *
JC	+27.30 (p< 0.001)	0.52	+0.41 *
JP	+13.18 (p< 0.001)	0.28 *	+0.22
JS	-6.86 (p< 0.001)	0.15	-0.13 *
LM	-19.76 (p< 0.001)	0.41	-0.30 *
MA	+7.68 (p< 0.001)	0.17 *	+0.14
RM	+5.58 (p< 0.001)	0.12 *	+0.19
RS	+29.77 (p< 0.001)	0.55	+0.44 *
TT	+8.74 (p< 0.001)	0.19	+0.15 *
WB	+21.01 (p< 0.001)	0.43	+0.42 *

Table 12: Eye Gain Data for Condition HR

NOTE: * Indicates first head tracking condition

SUBJ	HEAD GAIN DATA T-Test (p-value) Horizontal Head	HEAD GAIN DATA Corr. Coeff. (r) Horizontal Head	HEAD GAIN DATA Slope (m) Horizontal Head
DW	+2.44 (+0.015)	0.06	+0.03 *
FC	-2.74 (+0.006)	0.06	-0.07 *
JC	-39.39 (p< 0.001)	0.66	-0.70 *
JP	-24.27 (p< 0.001)	0.45 *	-0.44
JS	-21.16 (p< 0.001)	0.43	-0.42 *
LM	-40.12 (p< 0.001)	0.67	-0.66 *
MA	-4.14 (p< 0.001)	0.09 *	-0.08
RM	-3.02 (+0.003)	0.07 *	-0.04
RS	-61.21 (p< 0.001)	0.81	-0.85 *
TT	+16.43 (p< 0.001)	0.35	+0.19 *
WB	-48.68 (p< 0.001)	0.71	-0.75 *

Table 12: Head Gain Data for Condition 1

NOTE: * Indicates first head tracking condition

SUBJ	HEAD GAIN DATA T-Test (p-value) Horizontal Head	HEAD GAIN DATA Corr. Coeff. (r) Horizontal Head	HEAD GAIN DATA Slope (m) Horizontal Head
DW	+2.89 (+0.004)	0.06	+0.07 *
FC	+2.89 (+0.004)	0.06	+0.08 *
JC	-16.27 (p< 0.001)	0.34	-0.42 *
JP	-18.68 (p< 0.001)	0.39 *	-0.40
JS	-10.75 (p< 0.001)	0.24	-0.25 *
LM	-12.19 (p< 0.001)	0.27	-0.29 *
MA	-3.16 (0.002)	0.07 *	-0.06
RM	+14.28 (p< 0.001)	0.31 *	+0.19
RS	-51.49 (p< 0.001)	0.76	-0.80 *
TT	+18.18 (p< 0.001)	0.38	+0.44 *
WB	-30.76 (p< 0.001)	0.57	-0.58 *

Table 12: Head Gain Regression Data for Condition HT

NOTE: * Indicates first head tracking condition

SUBJ	HEAD GAIN DATA T-Test (p-value) Horizontal Head	HEAD GAIN DATA Corr. Coeff. (r) Horizontal Head	HEAD GAIN DATA Slope (m) Horizontal Head
DW	+8.10 (p< 0.001)	0.18	+0.17 *
FC	-2.11 (+0.035)	0.05	-0.06 *
JC	-24.68 (p< 0.001)	0.48	-0.61 *
JP	-19.64 (p< 0.001)	0.40 *	-0.45
JS	-18.32 (p< 0.001)	0.38	-0.42 *
LM	-20.04 (p< 0.001)	0.41	-0.50 *
MA	+0.98 (+0.329)	0.00 *	-0.02
RM	+14.21 (p< 0.001)	0.30 *	+0.21
RS	-59.20 (p< 0.001)	0.80	-0.89 *
TT	-1.86 (+0.064)	0.05	-0.03 *
WB	-45.10 (p< 0.001)	0.71	-0.72 *

Table 12: Head Gain Regression Data for Condition HR

NOTE: * Indicates first head tracking condition

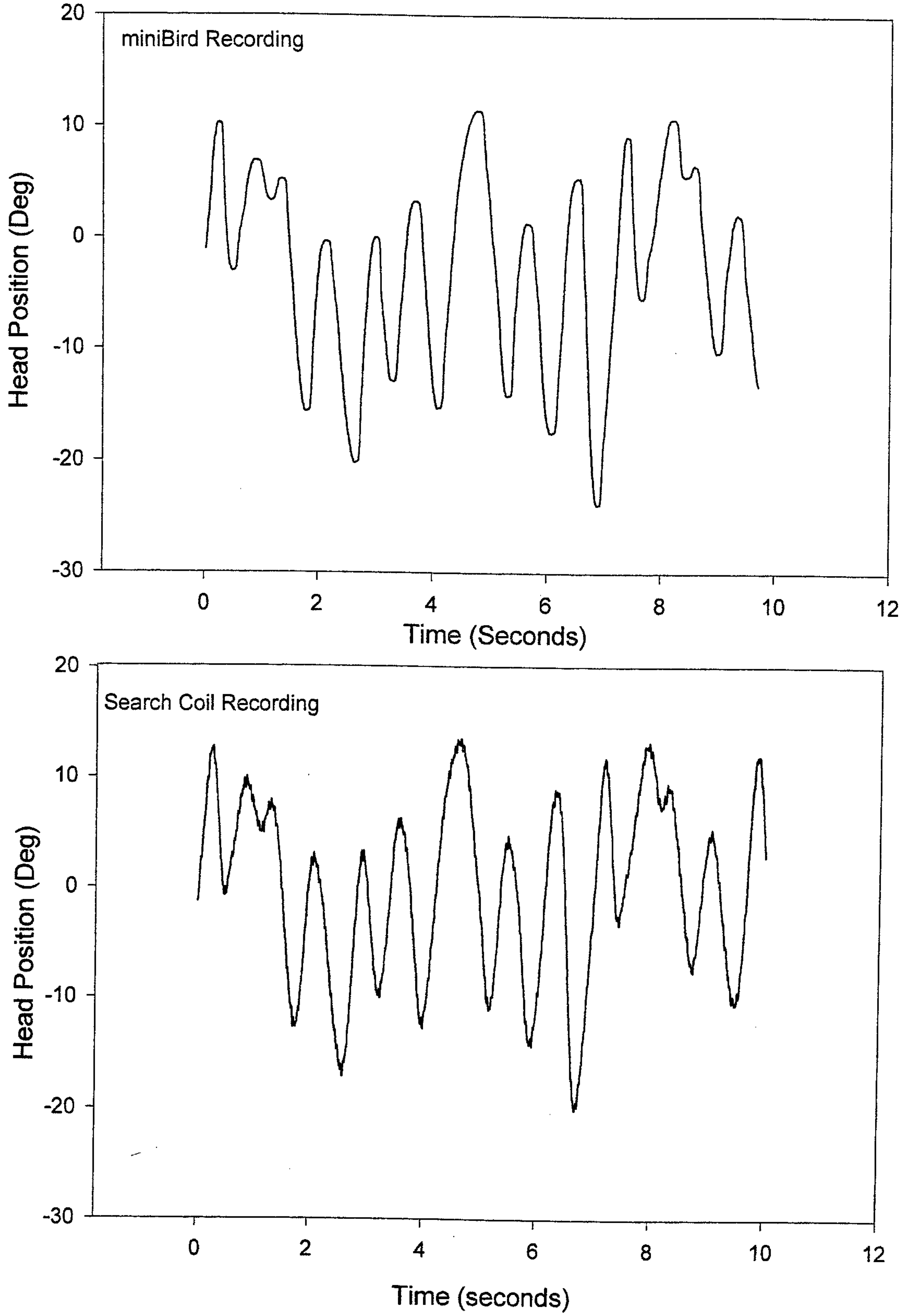

Figure 1: *miniBird* and Search Coil Recordings of Head Position
These data were recorded for 1 subject during the miniBird supplemental experiment

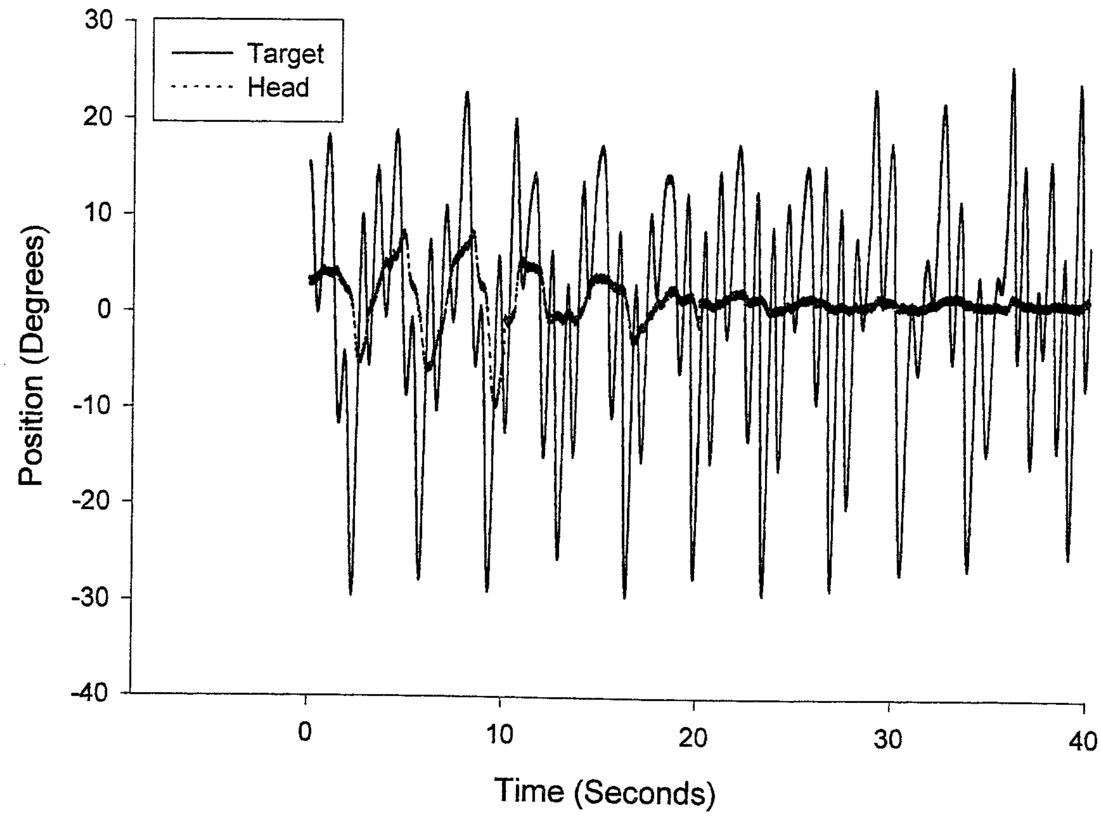

Figure 2: 40 second trace of target and head of subject WB during Condition

Note that WB initially moved head and then settled in to stationary head position

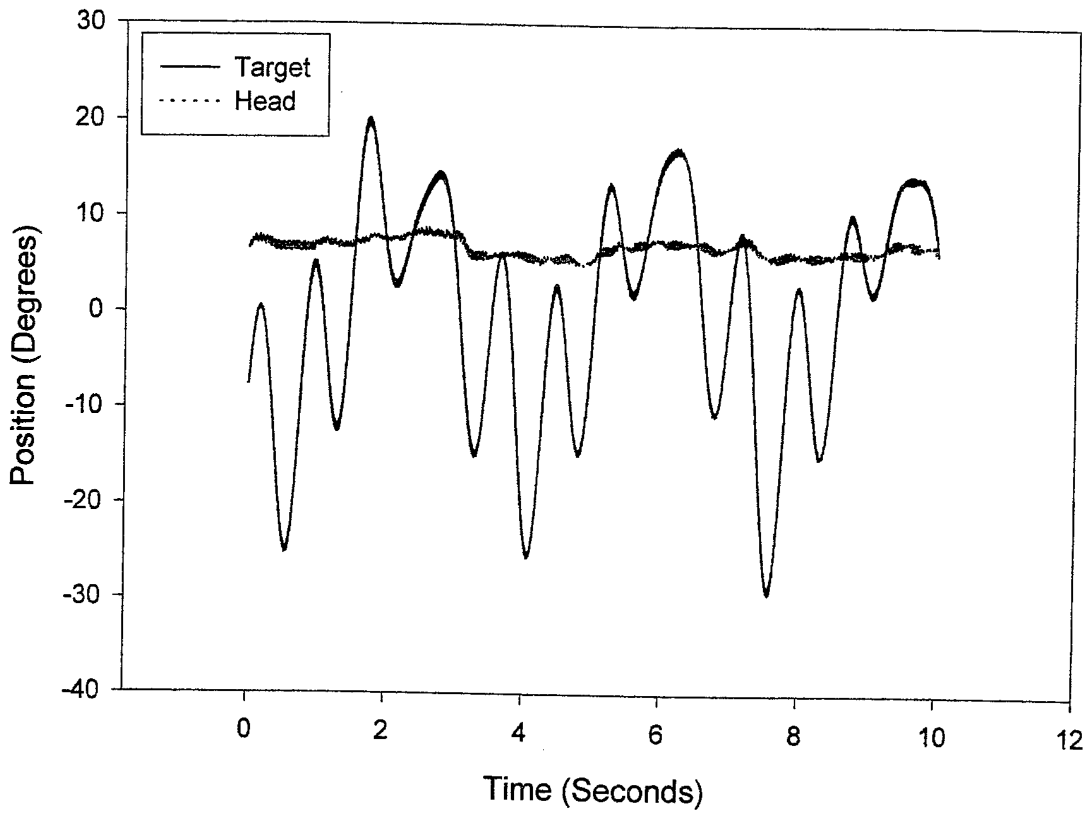

Figure 3: 10 second trace of target and head of subject LM during Condition 1

Note that subject's head is stationary and turned slightly to the right

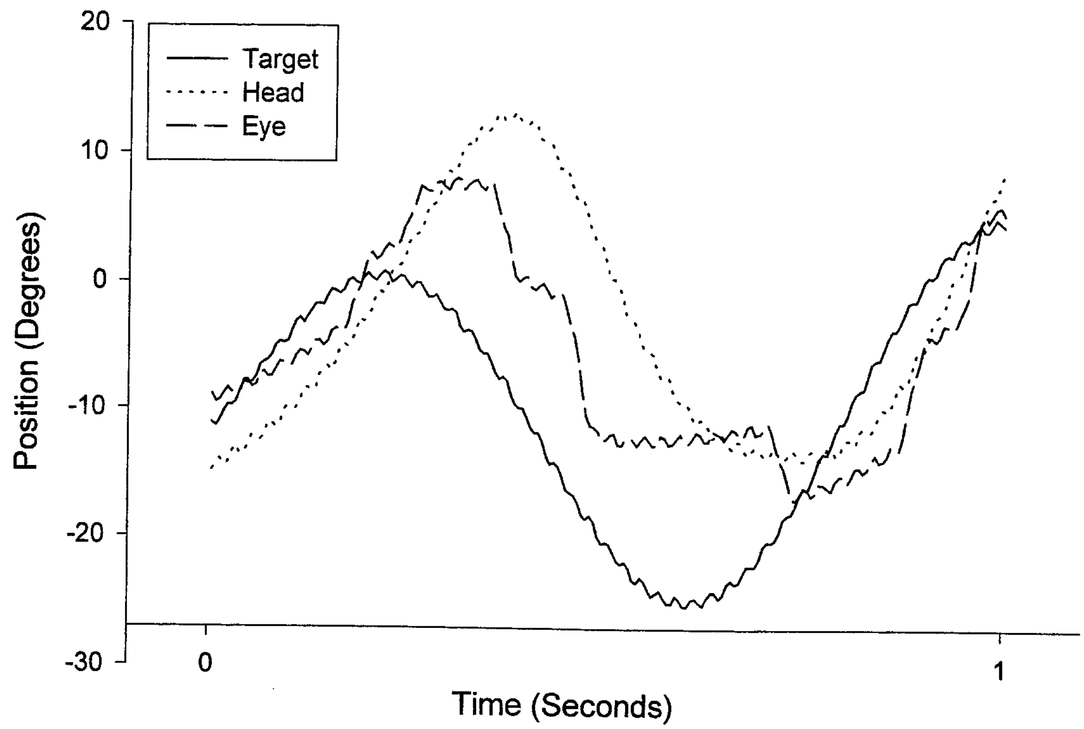

Figure 4
Data from HT Condition for Subject JC

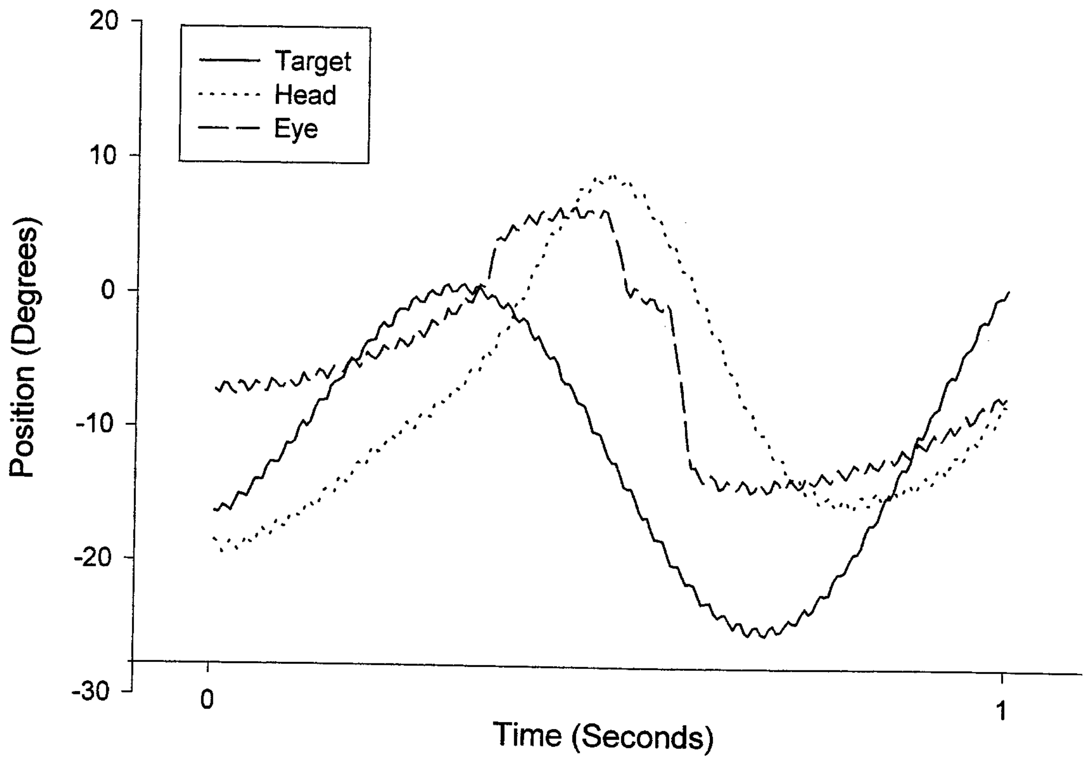

Figure 5
Data from HR Condition for Subject JC

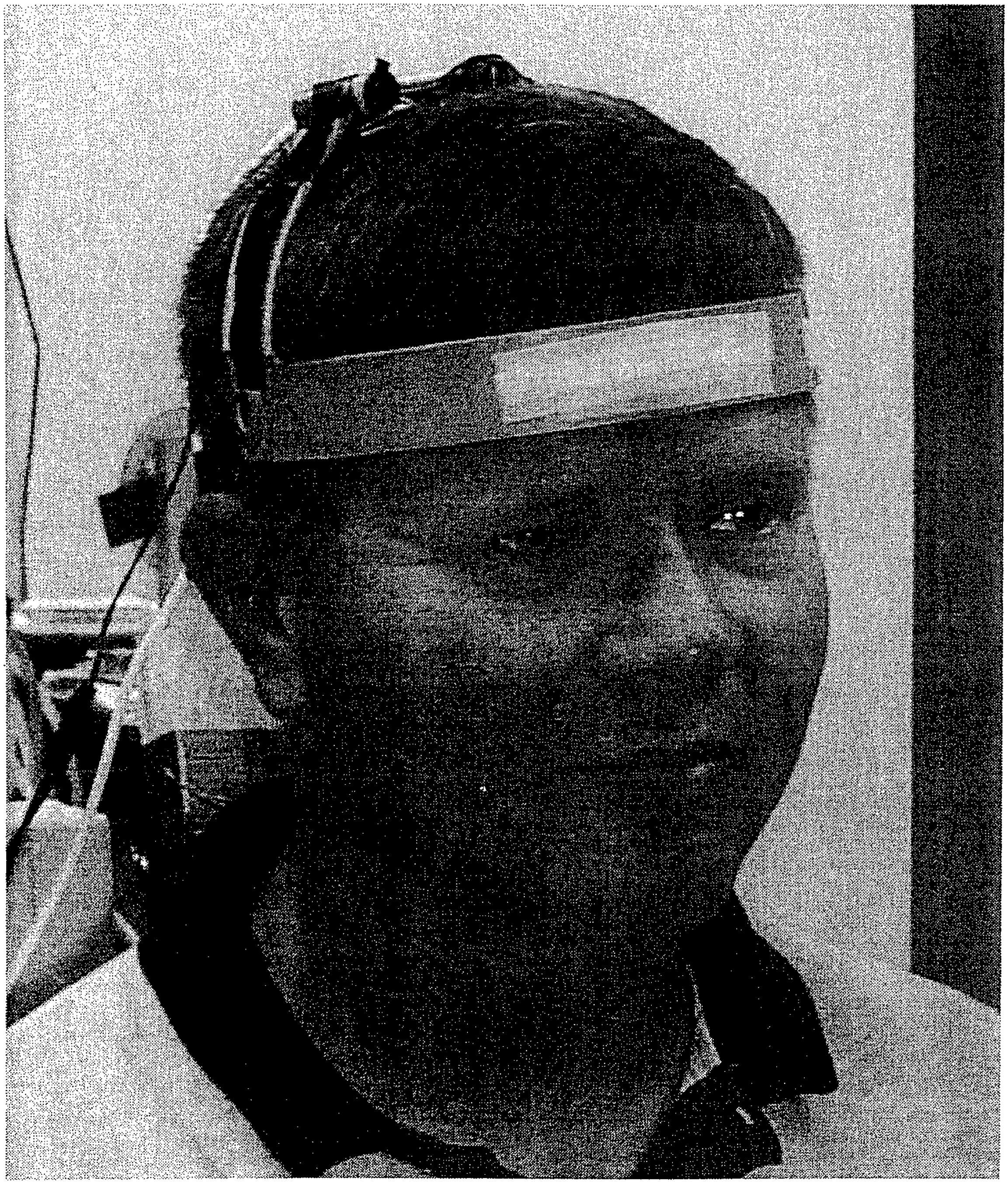

Figure 6. Photograph of apparatus. A laser is fixed to the head for Condition HR.

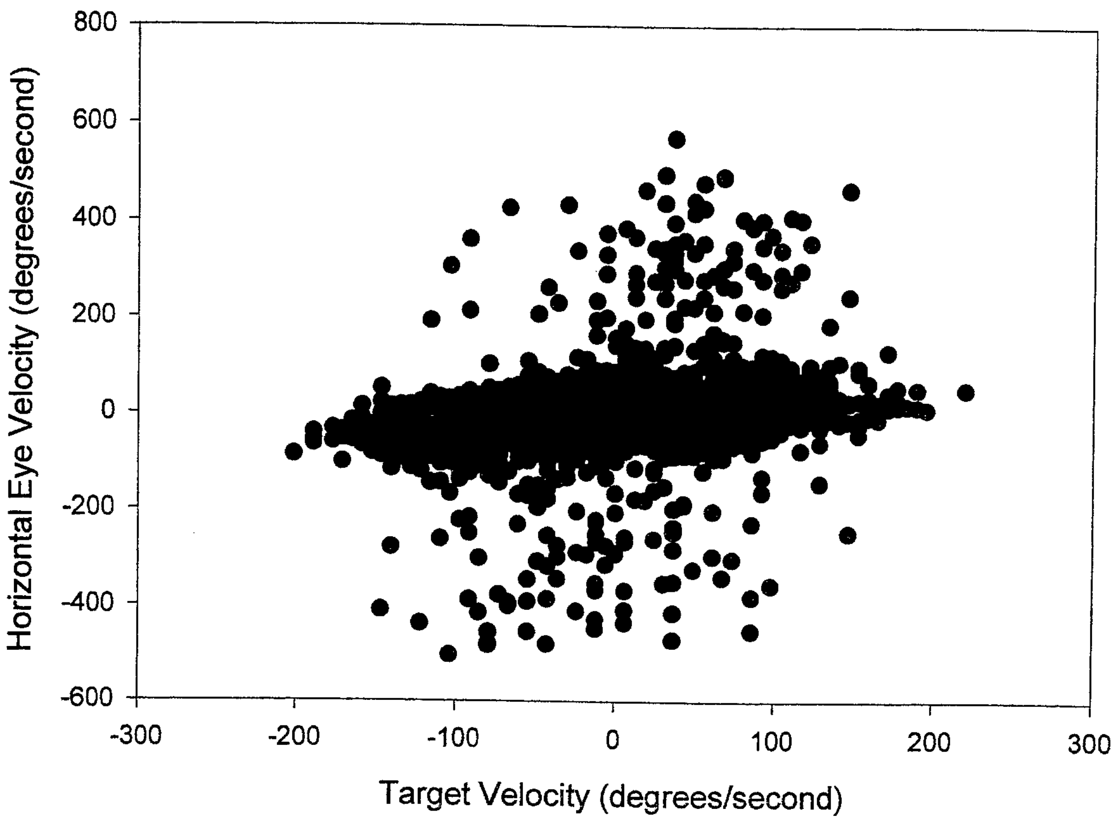

Figure 7: Plot of horizontal eye velocity versus target velocity for subject DW (Condition HT). Numerous saccadic outliers are evident.

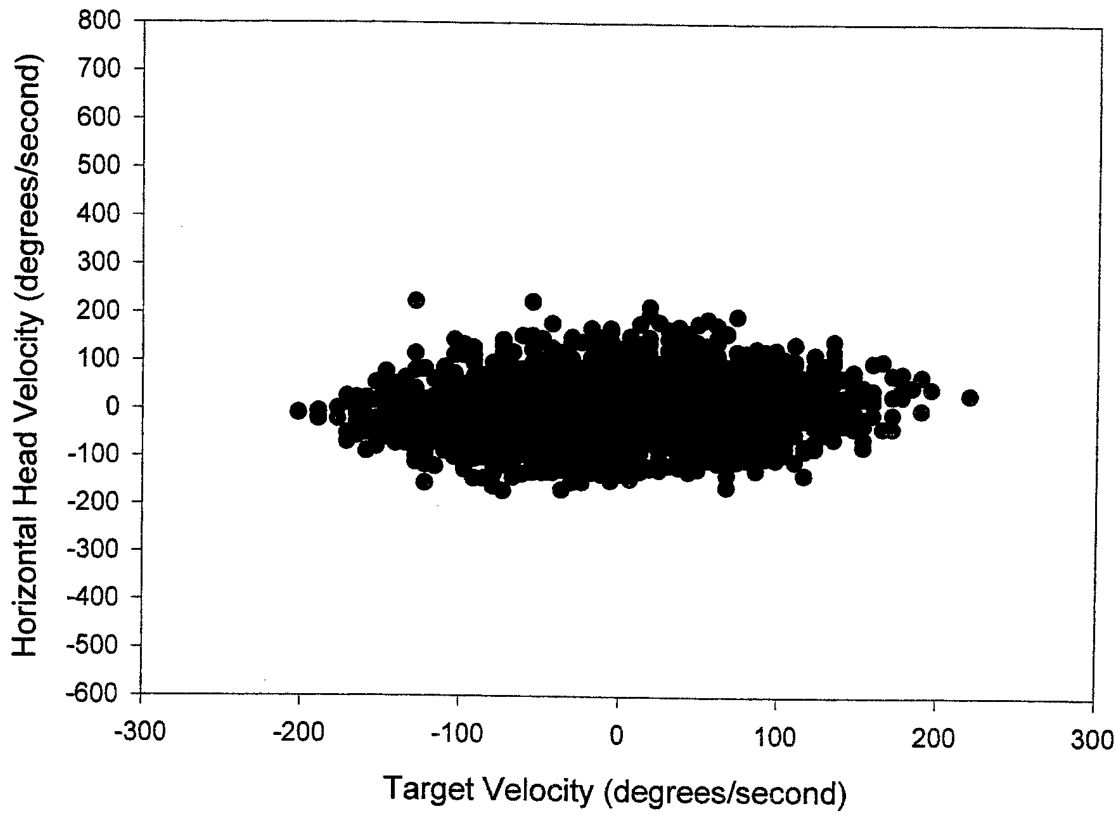

Figure 8. Plot of horizontal head velocity versus target velocity for subject DW (Condition HT).

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COMPARISON OF HEAD AND EYE TRACKING WITH AND WITHOUT A VISUAL CUE TO HEAD POSITION

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Little is known about the ability of humans to pursue pseudo-random targets with the head. This has important implications in the design of head-steered machinery. The purpose of this study was to determine the effect of a visual cue to head position on gaze and head pursuit.

Eleven subjects (3 females, 8 males) were studied as they tracked a pseudo-random horizontal one-dimensional laser target. The target consisted of the sum of six sinusoids. The frequency of the sinusoids was varied from 0.24 and 1.25 Hertz and each sinusoid had a randomly selected amplitude between 0.5 and 12 degrees. Three trials were run on each subject. For the first trial (Condition 1), each subject was instructed to follow the pseudo-random target using any combination of eye and head movement.

In the next two trials, subjects were told to either track the target with the head (Condition HT) or to maintain a head-fixed laser on the target (Condition HR). The order of trial two and trial three was randomized.

Gaze and head position signals were digitized at 200 Hertz using scleral search coils. The mean difference between head and target positions was 8.55 ± 1.15 degrees (Condition HT) and 8.99 ± 0.74 degrees (Condition HR). The mean head position differences were not significantly different for the two conditions. The mean eye position difference was significantly better in Condition HT than in Condition HR. Head and eye velocities were plotted against target velocity. A small linear relationship was usually present between these variables. The relationship was typically positive for the eye but could be positive or negative for the head. The results indicate that a visual cue to head position did not improve head pursuit performance, was detrimental to eye pursuit performance.

Furthermore, performance with the eye was always better than the head, implying that visually coupled machines should utilize eye tracking rather than head tracking.